Application of Air-Permeability Measurements to New Panama Canal

Taken from Section 11.3.3 of [Torrent et al, 2022]

The Panama Canal is a vital waterway to facilitate seaborne traffic between the Atlantic and Pacific oceans. Until 1914, year in which the Panama Canal was opened, ships travelling between both oceans have to sail round Cape Horn (South America), on waters that are particularly hazardous, owing to strong winds, large waves, strong currents and icebergs.

The Panama Canal Expansion is a huge civil engineering project (Fig. 1) that consists in expanding the capacity of the Panama Canal to handle more and bigger cargo ships (from Panamax to New Panamax vessels, than can double the cargo capacity). Basically, Panama Canal operates by raising the ships entering it from one ocean, through a series of locks, to the level of internal Gatun Lake, which is navigated till finding the opposite set of locks that brings down the ships again to the opposite ocean.

Fig. 1 – Massive concrete blocks of New Panama Canal

The Panama Canal Expansion project consists in building several structures, in particular two new sets of locks, one on the Atlantic mouth and the other on the Pacific mouth of the canal, that should "be safe, structurally sound, economical, practical, and durable, with minimum maintenance costs and fit for a design life of 100 years" [PCE Specs, 2008a]. The water in the locks that face the open seas have higher salinity than the others which have lower salinity as they take fresh water from the Gatun Lake.

Structural Marine Concrete structures are those directly exposed to saline water (lock walls, heads and floors, approach structures, water-saving basins and conduits, etc.) and are subjected to the specifications summarized in Table 1 for 100 years design service life [PCE Specs, 2008b].

Table 1 – Specifications for Structural Marine Concrete of Panama Canal Expansion

Minimum Cover	f'c	*w/c* ratio	Permeability (ASTM C1202)	28-d. Shrinkage (ASTM C157)	Peak T	*ΔT*	Curing
75 mm	Design	≤ 0.40	≤ 1'000 Coulombs	≤ 0.042 %	≤ 70 °C	≤ 20°C	≥ 7 d.

In addition, the following was stated: "The use of fly ash or ground granulated blast-furnace slag in the mixture is encouraged. Consideration shall be given to heat dissipation, permeability, setting time, strength gain, curing time, especially for mass concrete placements". Many structures, in particular the locks, are massive reinforced concrete structures (see Fig. 1, [Ferreira, 2014]) exposed to frequent wetting-drying cycles of contact with the fluctuating salty water level. Hence, restrictions on the drying shrinkage, peak temperature and difference ΔT between concrete and air temperature were specified in Table 1.

Initially, the binder used consisted of cement Type II [ASTM C150, 2012], to which a 'natural pozzolan' was added, the latter coming from grinding a basalt rock obtained from an external source. It has to be mentioned that the cement brand used for the Pacific locks was different than for the Atlantic locks, while the aggregates and 'natural pozzolan' were the same. More details on the project and concrete characteristics and processing in [Andrade et al, 2016].

From the very beginning it was realized that, even lowering the *w/b* ratio well below the specified maximum 0.40, to limits that put the workability of the mixes at risk, the set of materials chosen would not be capable of complying with the 1'000 Coulombs specified as maximum allowed chloride permeability.

The contractor failed to produce mix designs with [ASTM C1202, 2012] test results below the specified limit, seemingly due to the lack of activity of the so called 'natural pozzolan' which happened to be virtually inert. The contractor, on the other hand, suggested that the lack of compliance with ASTM C1202 was due to the basalt being electrically conductive. In order to investigate that claim, owner's consultants decided to incorporate another test to judge the quality of the mix designs being investigated, that was not influenced by the conductivity of materials and/or pore solution of the concrete. Naturally, since it was not included in the original specifications and tender documents of the project, this test could not be used for compliance control, but to provide further information that could help decide whether the mixes proposed by the contractor were likely to ensure 100 years' service life of the project or not.

The chosen method was the air-permeability kT, with the Panama Canal Administration (ACP) acquiring two units of the *PermeaTORR* (M-A-S Ltd.), one for the Atlantic and the other for the Pacific side of the Canal. Fifteen members (engineers and technicians) of the quality control personnel were trained by Prof. Fernández Luco (Univ. of Buenos Aires) on theoretical and practical aspects of the measurement of air-permeability, later complemented by a visit of R. Torrent to confirm that the instruments were being used correctly, both in the laboratory and on site.

Just a few of the huge amount of quality control results obtained, made availability to the authors, will be discussed here, as much information is until now still classified. Fig. 2 presents the correlation between the charge passed Q and kT for 92 pairs of data, among which are laboratory data from the Pacific side (Set 34) and the Atlantic side (Set 35) of the Canal, shown in red symbols. The results of the Canal merge reasonably well with those obtained from other sources, although it can be observed that most Atlantic results fall below the regression line whilst those of the Pacific side lie close to the regression line. The average of Q and the geometric mean of kT are:

Atlantic side: Q_m = 774 Coulombs ; $kT_{gm} = 0.018 \times 10^{-16}$ m²

Pacific side: Q_m = 1721 Coulombs ; $kT_{gm} = 0.051 \times 10^{-16}$ m²

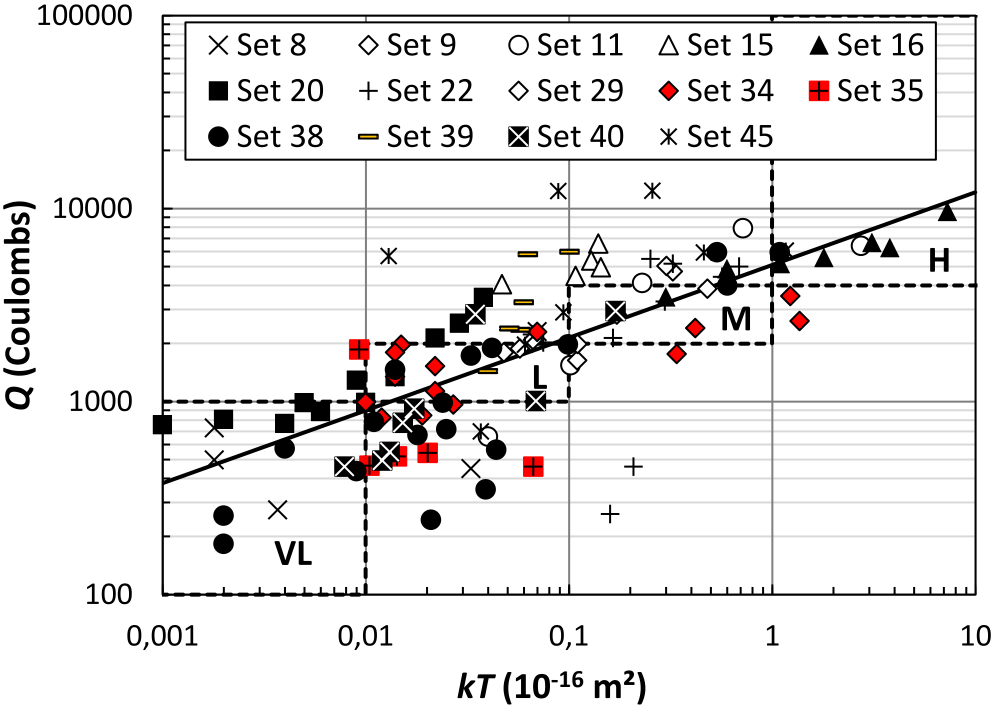

Fig. 2 - Correlation between electric charge *Q* passed in ASTM C1202 'RCPT' test and *kT*

The results confirm that the concrete produced in the Atlantic side is less permeable than that of the Pacific side, but discard the alleged effect of the conductivity of the basalt, as the results tend to follow the general trend of Fig. 2.

During the visit and training by R. Torrent, nine measurements were conducted *in situ* on one Block ('A'). One aspect to remark is that the surface moisture *m*, measured with a *Concrete Encounter* instrument, showed values not exceeding 5.5% (on the sunny side of the block) despite two rainy days preceding the day of test, in a tropical climate. The shadow side, on the contrary, showed values above 5.5%. The air-permeability *kT* measured on eight out of the nine points showed uniform, quite acceptable low values. One point showed a high *kT*, measured in a zone of the block where some segregation was visible. Unfortunately, these optimistic results were not confirmed by tests performed on other blocks, as shown in Table 2 [Torrent, 2011]. Indeed, blocks 'B' and 'C' showed high values of both kT_{gm} and s_{LOG}, opening some questions on their potential durability. As indicated in [Torrent, 2011], inappropriate consolidation with poke vibrators was observed during the visit, as well as serious honeycombing of a neighbouring block that was being stripped while *kT* testing of block 'A' was in progress (Fig. 3).

Table 2 – On site air-permeability *kT* tests results obtained on three blocks (Pacific Side)

Block	N	kT_{gm} (10^{-16} m²)	s_{LOG}
'A'	8	0.012	0.19
'A'	9	0.020	0.66
'B'	12	1.353	0.77
'C'	5	0.468	0.49

Finally, the use of *kT* test to explore different alternatives to optimize the concrete binder is shown in Fig. 4 where the impact of the addition of several SCMs on *kT* was investigated. Designation (A) and (P) indicate the use of materials from the Atlantic and Pacific side, respectively.

Fig. 3 – Honeycombing in stripped block of New Panama Canal

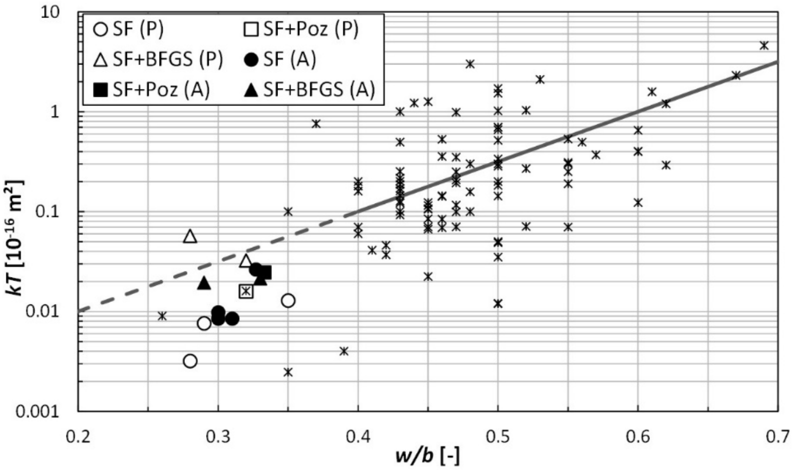

Fig. 4 – Relation between *kT* and *w/b* ratio for New Panama Canal concretes

The addition of silica fume (SF) alone and, to a lesser extent, in combination with the pozzolan in use (Poz) or with blast-furnace granulated slag (BFGS), looks very effective in reducing the permeability of concretes with very low *w/b* ratios. The chart in Fig. 4 shows previous data (∗) and the CEB-FIP relation (p. 2-52, Eq. {2.1-107} of [CEB-FIP, 1991]), valid in the range 0.4 < *w/c* < 0.7, extrapolated as dotted line:

$$\log_{10} K_g = -(19 - 5\,.w/c) \tag{1}$$

where

K_g = gas-permeability (m²)

An expert, invited by the owner in May 2011, proposed the immediate use of Silica Fume along with a drastic reduction in ground basalt (‘pozzolan’) content, as the most effective solution. As a result, Silica Fume was incorporated into the mix designs for Marine Structural Concrete and ground basalt reduced to a minimum. In [Andrade et al, 2014; Andrade et al, 2016] a durability assessment approach is described, based on bulk diffusion and electrical resistivity tests (both described in Annex A) performed on cast cylinders moist cured during several months. As the results in Table 2 show, such assessment needs to be complemented by site testing to verify the durability quality of the end-product.

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